

LC-3 Assembly Language

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BỞI HCMUT-CNCP
(Textbook Chapter 7)



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Assembly and assembler

- Machine language - binary
- Assembly language - symbolic
- Assembler is a program that turns symbols into machine instructions.
 - ISA-specific: close correspondence between symbols and instruction set
 - mnemonics for opcodes
 - labels for memory locations



Syntax of LC-3 assembly: Language elements

- Instructions (we have seen most of them)
 - Comments
 - Labels
 - Declarations
 - Assembler directives and trap codes
- Whitespaces (between symbols) and case are ignored.



Instructions

- One instruction or declaration per line

LABEL OPCODE OPERANDS ; COMMENTS



Opcodes and Operands

- **Opcodes**

- reserved symbols that correspond to LC-3 instructions
- listed in Appendix A (ex: **ADD**, **AND**, ...)

- **Operands**

- **Registers:** R_n , where n is the register number
- **Immediate numbers:** $\#n$ (decimal), $\#n$ (hex), or $\#n$ (binary)
- **Labels:** symbolic names of memory locations
- Operands are separated by spaces, tabs, or commas
- Their number, order, and type correspond to the instruction format



Data types

LC-3 has 2 basic data types

- Integer
- Character

Both are 16 bits wide (a word), though a character is only 8 bits in size.



Comments

- Anything on a line after a semicolon is a comment
- Comments are ignored by assembler
- Used by humans to document/understand programs
- Tips for useful comments:
 - avoid restating the obvious, as "decrement R1"
 - provide additional insight, as in "accumulate product in R6"
 - use comments to separate pieces of program



Labels

- Placed at beginning of line
- Assign a symbolic name to their **line** (its address)
- Symbolic names used to identify **memory locations**. Two kinds:
 - Location of **target** of a branch or jump
 - Location of a **variable** for loading and storing
- Can be 1-20 characters in size



Assembler directives

- **Directives or psuedo-ops** give information to the assembler.
- Not executed by the program
- All directives start with a period '.'

Directive	Description
.ORIG	Where to start in placing things in memory
.FILL	Declare a memory location (variable)
.BLKW	Declare a group of memory locations (array)
.STRINGZ	Declare a group of characters in memory (string)
.END	Tells assembly where your program source ends



.ORIG

- Tells simulator where to put your code in memory (starting location)
- Only one **.ORIG** allowed per program module
- PC is set to this address at start up
- Similar to the `main()` function in C
- Example: the standard convention is

```
.orig    x3000
```



.FILL

- Declaration and initialization of variables
- One declaration per line
- Always declaring words
- Examples:

flag	.FILL	x0001
counter	.FILL	x0002
letter	.FILL	x0041
letters	.FILL	x4241



In C

type varname ;

.FILL

Where type is

int (integer)

char (character)

float (floating-point)

In LC-3

varname .FILL value

- value is required (initialize)
- type is only 16-bit integer



.BLKW

- Reserves (and initializes) a sequence of contiguous memory locations (arrays)
- Examples:

```
;set aside 3 locations  
    .BLKW      3
```

```
;set aside 1 location and label it  
Bob    .BLKW      1
```

```
; set aside 7 locations,  
; label them, and init them all to 4  
Num    .BLKW      7      #4
```




. STRINGZ

- Declare a string of characters
- Automatically terminated with x0000
- Example:

hello .STRINGZ "Hello World!"

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x0048

x0065



. END

- Tells the assembler where your program ends
- Only one **.END** allowed in your program module
- That's where the assembler stops assembling, NOT where the execution stops!

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TRAP

(System Calls)

Very tedious and dangerous for a programmer to deal with I/O.

This is why we like to have an OS.

Need an instruction to get its attention.

Use the **TRAP** instruction and a *trap vector*.



Trap Service Routines

The LC-3 assembler provides “pseudo-instructions” for each trap code, so you don’t have to remember them.

Trap Vector	Assembler Name	Usage & Result
x20	GETC	Read a character from console into R0, not echoed.
x21	OUT	Write the character in R0[7:0] to console.
x22	PUTS	Write string of characters to console. Start with character at address contained in R0. Stops when 0x0000 is encountered.
x23	IN	Print a prompt to console and read in a single character into R0. Character is echoed.
x24	PUTSP	Write a string of characters to console, 2 characters per address location. Start with characters at address in R0. First [7:0] and then [15:0]. Stops when 0x0000 is encountered.
x25	HALT	Halt execution and print message to console.



To print a character

; the char must be in R0[7:0]

TRAP x21

or

OUT

Trap Examples

To end the program

To read in a character

; will go into R0[7:0],

; no echo.

TRAP x20

or

GETC

TRAP x25

or

HALT



Simple LC-3 program

```
.ORIG x3000
LD    R2, Zero
LD    R0, M0
LD    R1, M1
Loop  BRz   Done
      ADD   R2, R2, R0
      ADD   R1, R1, -1
      BR    Loop
Done  ST     R2, Res
      HALT

Res   .FILL x0000
Zero  .FILL x0000
M0    .FILL x0007
M1    .FILL x0003
      .END
```

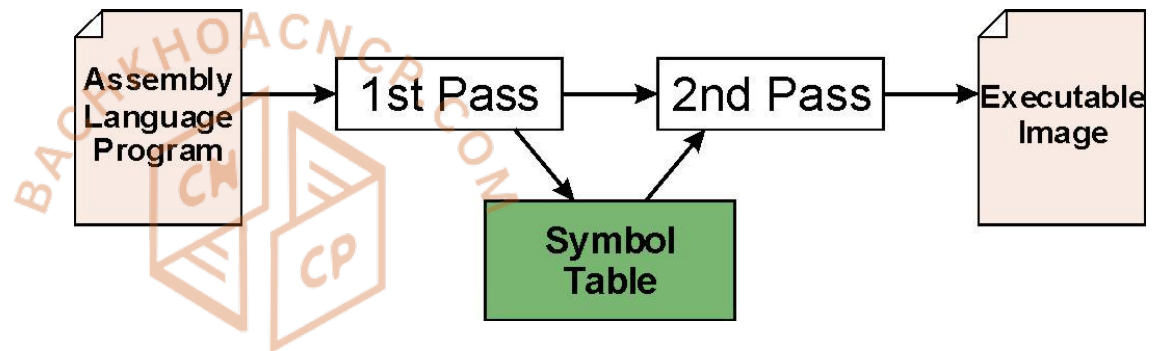
What does this
program do?

What is in Res at
the end?



The assembly process

- Convert assembly language file (.asm) into an executable file (.obj) for the LC-3 simulator.



- **First Pass:**
 - scan program file
 - find all labels and calculate the corresponding addresses - the symbol table
- **Second Pass:**
 - convert instructions to machine language, using information from symbol table



First Pass: The Symbol Table

1. Find the `.ORIG` statement, which tells us the address of the first instruction.
 - Initialize **Location Counter (LC)**, which keeps track of the current instruction.
2. For each non-empty line in the program:
 - a) If line contains a label, add label and LC to **symbol table**.
 - b) Increment LC.
 - NOTE: If statement is `.BLKW` or `.STRINGZ`, increment LC by the number of words allocated.
3. Stop when `.END` statement is reached.

NOTE: A line with only a comment is considered an empty line.



Practice: Symbol Table

Build the symbol table for the multiply program:

Symbol	Address

```

        .ORIG    x3000
x3000   LD      R2, Zero
x3001   LD      R0, M0
x3002   LD      R1, M1
        ; begin multiply
x3003   Loop    BRz    Done
x3004           ADD    R2, R2, R0
x3005           ADD    R1, R1, #-1
x3006           BR     Loop
        ; end multiply
x3007   Done    ST      R2, Result
x3008           HALT
x3009   Result  .FILL   x0000
x300A   Zero    .FILL   x0000
x300B   M0      .FILL   x0007
x300C   M1      .FILL   x0003
        .END
    
```



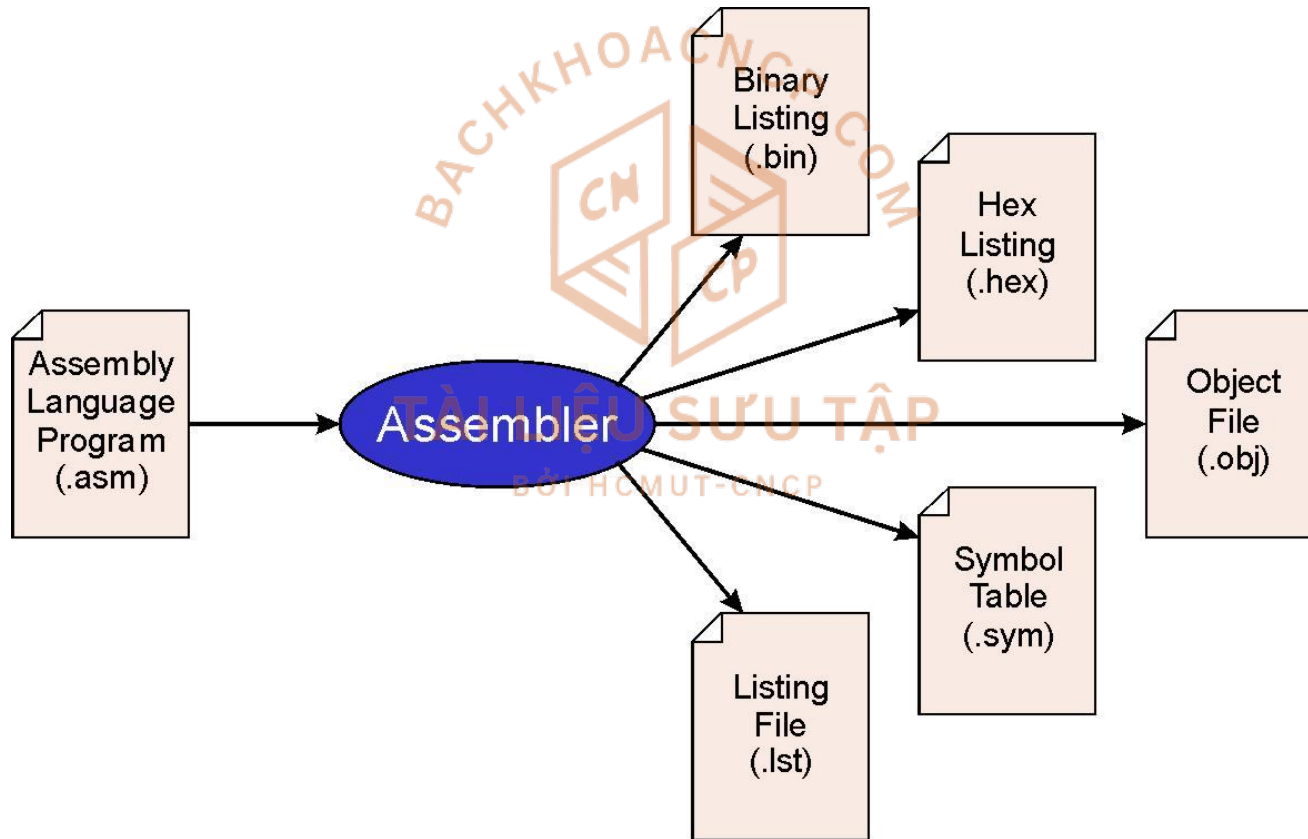
2nd Pass: Generating Machine Language

- For each executable assembly language statement, generate the corresponding machine language instruction.
 - If operand is a label, look up the address from the symbol table.
- **Potential problems:**
 - Improper number or type of arguments
 - ex: `NOT R1, #7`
`ADD R1, R2`
 - Immediate argument too large
 - ex: `ADD R1, R2, #1023`
 - Address (associated with label) more than 256 from instruction
 - can't use PC-relative addressing mode



The LC-3 Assembler

- Using "assemble" (Unix) or LC3Edit (Windows), generates several different output files.



Multiple Object Files

- An object file is not necessarily a complete program.
 - system-provided library routines
 - code blocks written by multiple developers
- For LC-3 simulator, can load multiple object files into memory, then start executing at a desired address.
 - system routines, such as keyboard input, are loaded automatically
 - loaded into "system memory," below x3000
 - user code should be loaded between x3000 and xFDFF
 - each object file includes a starting address
 - be careful not to load overlapping object files



Linking

Linking is the process of resolving symbols between independent object files.

- Suppose we define a symbol in one module, and want to use it in another
- The directive `.EXTERNAL` is used to tell the assembler that a symbol is defined in another module
- The linker will search symbol tables of other modules to resolve symbols and complete code generation before loading



Loading

- *Loading* is the process of copying an executable image into memory.
 - more sophisticated loaders are able to relocate images to fit into available memory
 - must readjust branch targets, load/store addresses

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Running

- The loader makes the CPU jump to the first instruction -> .ORIG.
- The program executes
- When execution completes, control returns to the OS or to the simulator
- Load again to run again with different data (in LC3 we must **assemble again**, since data is in program)



Recommended exercises:

- Ex 7.1 to 7.5, 7.7 to 7.9
- *Especially recommended*: 7.13 to 7.15, and 7.18 to 7.24 (yes, all of them except 7.16 and 7.17)

